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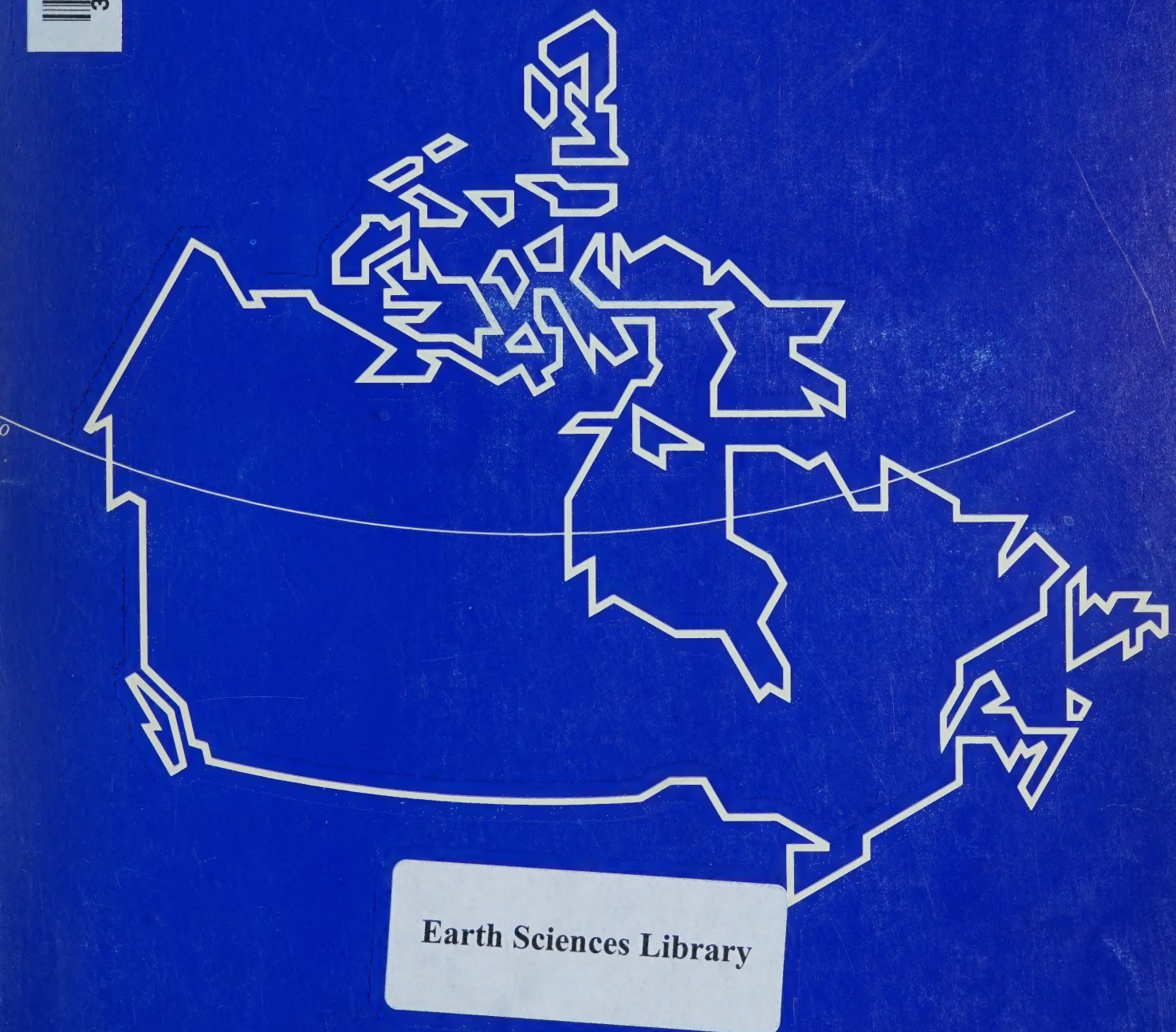
Sump Studies: I
Terrain Disturbances



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Environmental Studies No. 6

Sump Studies: I
Terrain Disturbances

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Cette publication peut aussi être obtenue en français.

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SUMMARY

Forty-seven abandoned wellsites in the Mackenzie Delta and Arctic Islands are analysed with respect to terrain and land use problems encountered. Approximately 30% of the sites visited experienced problems related either directly or indirectly to sumps and/or the containment of waste drilling fluids. These problems are classified as follows: (1) Type A - non-containment during drilling, (2) Type B - melt-out problems during summer operations, and (3) Type C - restoration problems. Type C problems are the most common and include sump subsidence and collapse, non-containment of fluids during sump infill, subsurface leakage of fluids, and excessive terrain disturbance adjacent to the sump. The least problems appear associated with one-season winter drilling operations. Two-season winter drilling, in which the sump is left open during the summer, and one-season summer drilling operations usually present more problems.

A number of possible alternate sump fluid disposal methods are mentioned. These include the direct disposal of fluids upon tundra in certain instances, notably polar desert environments, dilution into water bodies in certain flood plain and coastal locations, and the trucking of fluids to central containment sites.

I. THE ALUR SUMP PROJECT

The primary objective of the ALUR sump project is to provide environmental and geotechnical information related to the construction, use and subsequent restoration of sumps in different permafrost and terrain situations. A secondary objective is to assess alternate methods of disposing of waste drilling fluids, and particularly, direct spillage on the tundra. A further, long term, objective is to evaluate the effectiveness of the Territorial Land Use Regulations in controlling the drilling of oil and gas wells in permafrost and the disposal of drilling fluids.

The project has four phases:

1. The first phase, which is reported on here, was undertaken during the summers of 1976 and 1977. It consisted of a survey of wellsites in the Arctic, of varying ages and located in a variety of terrain and permafrost environments. The objectives were to document the performance of these sumps, to develop case histories of sump problems where these were evident, and to identify localities where drilling without a sump may have been preferable.

2. The second phase was initiated during the winter of 1976-1977. It consisted of the instrumentation of two sumps in order that the thermal, permafrost and geomorphic changes associated with the operation, restoration and subsequent abandonment of the sumps could be monitored over a three year period. A sump, at the Panarctic Oils Ltd. Bent Horn 1-01 wellsite on Cameron Island was instrumented in October 1976. A second sump at the Gulf Canada Ltd. Ogruknang M-31 wellsite in the Caribou Hills, Mackenzie Delta, was instrumented in April 1977.

   Of particular interest were (a) the influence of sump fluids upon permafrost thermal regimes, (b) the determination of whether or not sump fluids freeze in situ, and the time period involved, and (c) the nature and extent of any thermokarst activity that might result.

3. A third phase involved the development of numerical simulation models illustrating the thermal effects of sump fluids upon the enclosing permafrost. The models generated were tested against the field data obtained from the instrumented sites.

4. The fourth phase of the project involved an investigation into the toxicity of waste drilling fluids to plants. An experimental spill of sump fluids was undertaken at the Gulf Siku-21 site in the Mackenzie Delta in January 1978 in a locality where a detailed botanical and site survey had been made the previous summer. In addition, visits to a number of old wellsites in both the High Arctic Islands and the Mackenzie Delta were made during the summer of 1977 to investigate and document the effects of leakage of drilling fluids on plant communities adjacent to the sumps.

II. INTRODUCTION - PHASE I

Personnel involved in the ALUR sump project are Dr. H.M. French, Department of Geography and Regional Planning, University of Ottawa, responsible for project co-ordination and field studies, Dr. M.W. Smith, Department of Geography, Carleton University, responsible for computer simulation work and field studies, and Dr. D. Smith, Department of Botany and Genetics, University of Guelph, responsible for the biologic and toxicity aspects.

A second report in the series describes the thermal monitoring programs undertaken at the Bent Horn I-01 and Gulf Ogruknang M-31 sites, and will compare the field data with computer simulated data (Phases 2 and 3). A third report dealing with Phase 4, will describe the extent of the toxicity of sump fluids to vegetation.

III. SUMP SURVEY

Over 40 active or abandoned wellsites were visited during the summer of 1976. The majority were examined on the ground. The available logistics determined which sites were selected. Although they comprise only a small fraction of the wells drilled in the N.W.T., they represent a wide range of terrain and permafrost conditions. At each site a general assessment of geomorphic, permafrost and terrain conditions was made. First, observations were made of surficial materials, depth of thaw, ground ice and moisture conditions, and the thermal effects of any surface organic cover upon active layer temperatures and average thaw depths. Second, the condition of the sump was noted, and observations made as to the degree of restoration, any post restoration slumping, and any leakage of sump fluids. Third, any current geomorphic activity associated with, or likely to affect the sump was noted.

At certain sites, case histories were compiled using the relevant land use permit files of IAND, the field reports of N. Peterson (1976 a, b and c), and industry sources in Calgary.

In 1977, the sump survey was continued with a visit to the U.S. National Petroleum Reserve No. 4, on the Alaska North Slope and the reexamination of wellsites on Banks and Cameron Islands.

The wellsites visited in 1976 and 1977 are listed in Appendices I and II. Site locations are shown in Figures 1, 2, 3 and 9.

1. Western Arctic Islands

The western Arctic Islands exhibit a range of environments. At one extreme are relatively well vegetated tundra lowlands (e.g. southern Banks Island). At the other extreme are the barren and arid polar deserts of islands such as Prince Patrick or Ellef Ringnes. Areas of transition, where tundra and polar desert environments intermix are found in such places as northern Banks Island and southern Melville Island. In addition, small areas of relatively luxurious tundra exist, as Arctic "oases", within the polar desert environment. These oases often reflect local geology and/or topography and examples include southwest Cameron Island (e.g. Bent Horn) and parts of Bathurst Island (e.g. Bracebridge Inlet).

An attempt was made to consider all of these environments.

(i) Banks Island

Six sites were visited, four of which had been examined the previous year. None are potential oil or gas wells, and few exceed 10,000 feet in depth.

Panarctic Elf Bar Harbour E-76

The site is located on the northwestern extremity of the Beaufort Plain, a flat featureless surface developed in sand

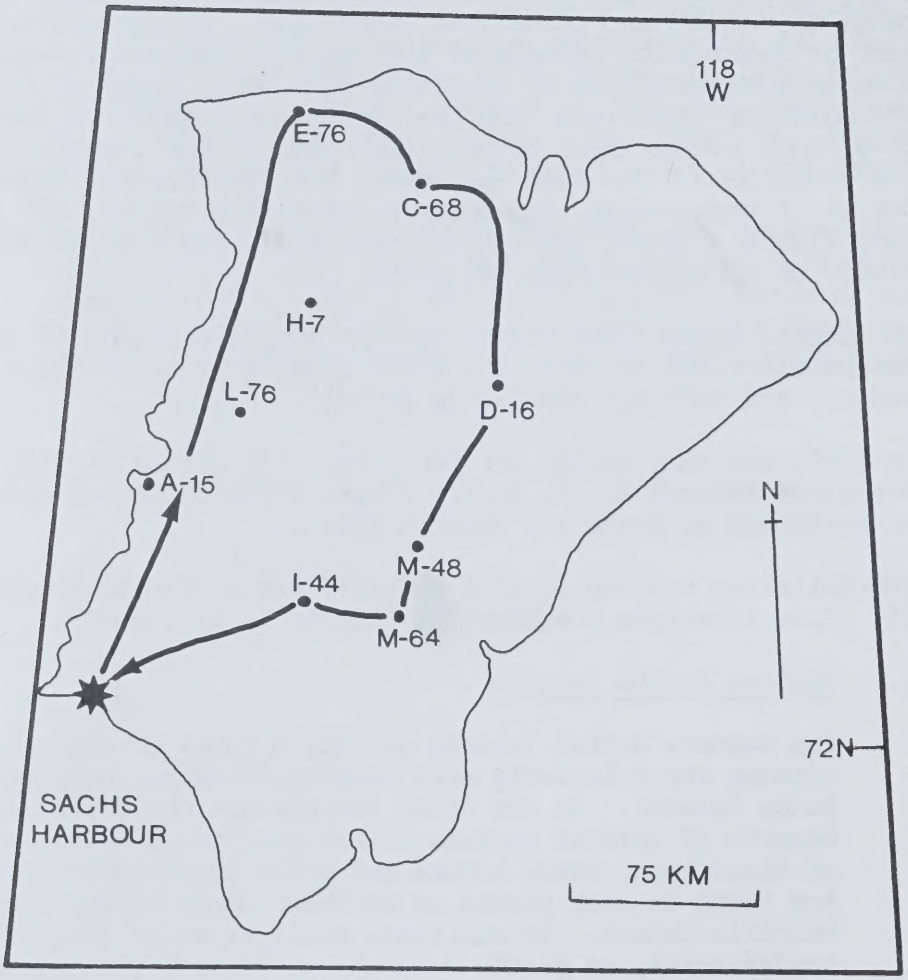

Fig. 1. Traverses made on Banks Island, July 8-10, 1976

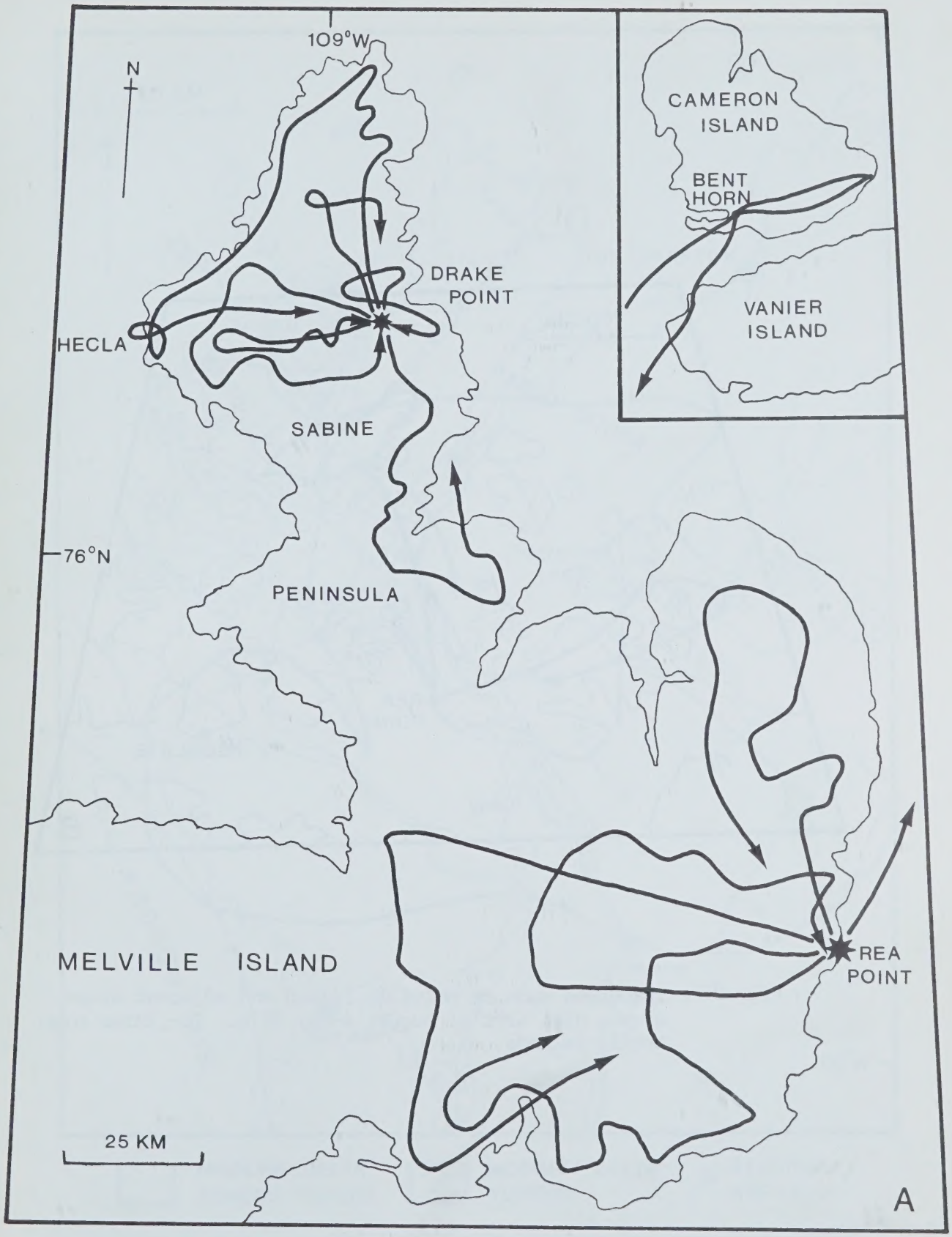

Fig.2 Traverses made on Melville Island and adjacent areas of the high Arctic, August 4-11, 1976. A - East Melville Island and Sabine Peninsula.

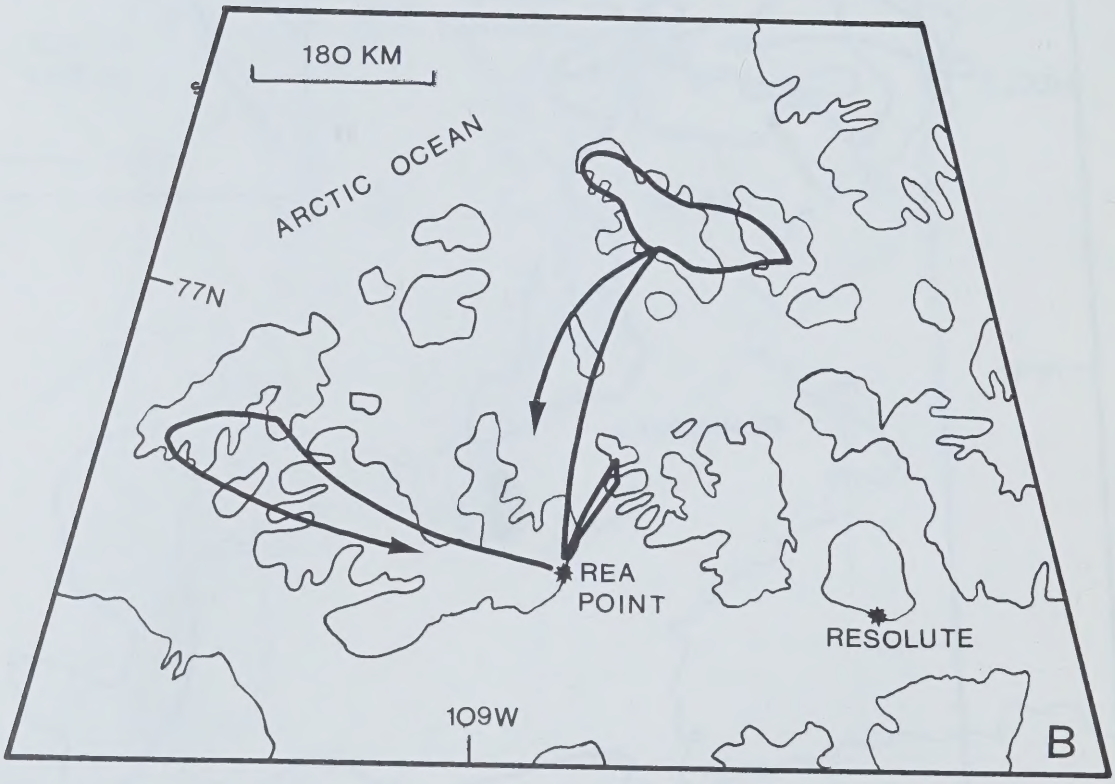

Fig. 2(b) Traverses made on Melville Island and adjacent areas of the high Arctic, August 4-11, 1976. B - Other high Arctic islands.

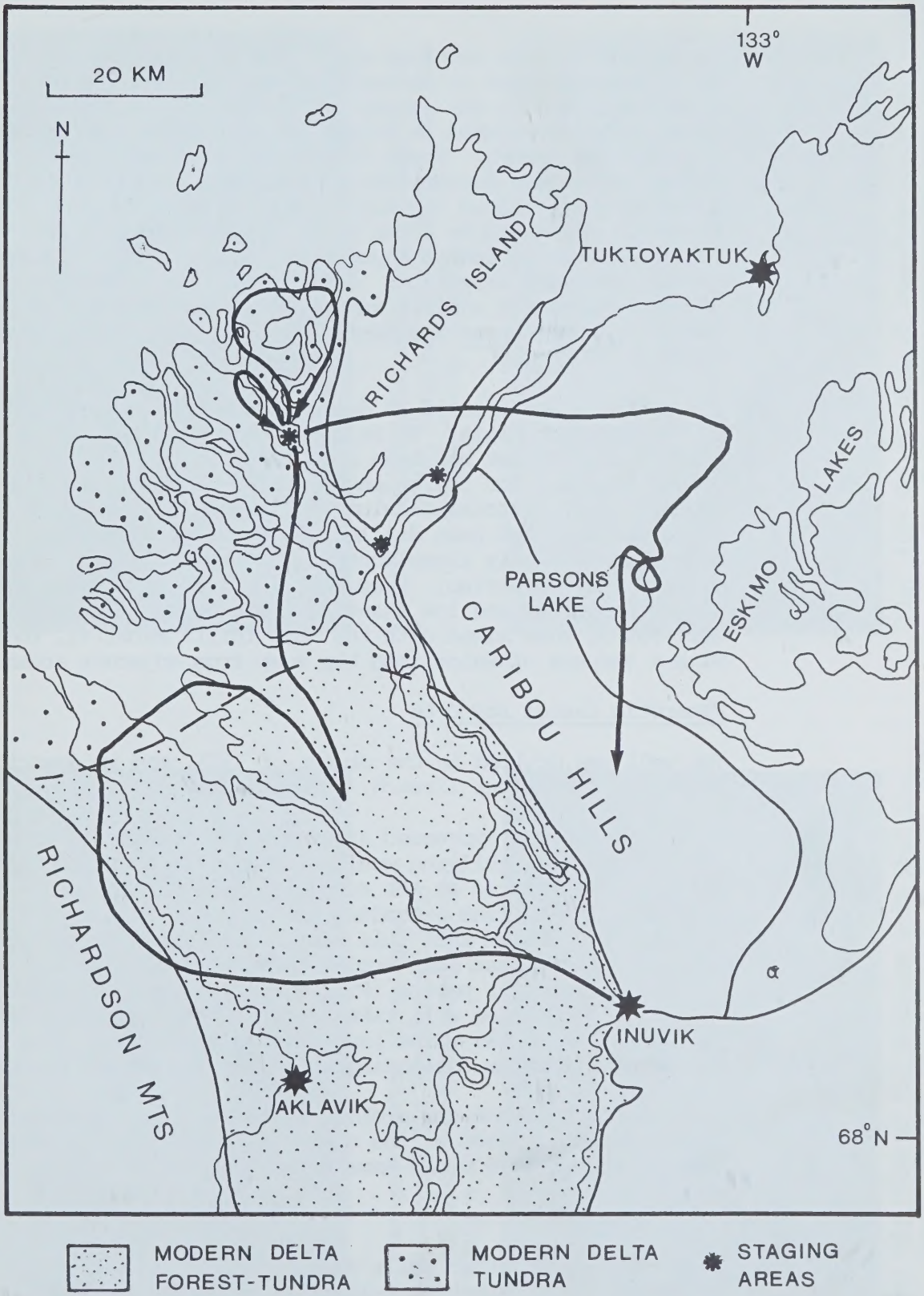

Fig. 3. Traverses made in Mackenzie Delta, September 7-11, 1976.

and gravel of Late Tertiary age. Slight topographic differences are important in determining humidity and vegetation characteristics on the ground. Lines of subsurface seepage exist probably related to slight variations in permeability of the sand and gravel. These factors interact to form large, almost indistinct depressions possessing a near continuous cover of moss, lichen and wet tundra grasses. Such areas are separated by areas where drier conditions prevail, related either to subtle topographic changes or to variability in the surficial materials. Typically, these areas are devoid of vegetation, and exhibit mud polygons and desiccation cracking with occasional Dryas and Saxifrage colonising these gravelly barrens.

The wellsite was located in one of the damper, vegetated areas of the Beaufort Plain. In an attempt to minimize damage, the surface organic mat had been scraped clear of the site and heaped together for use in restoration. The sump exhibited signs of post restoration slumping (Figure 4 a) and waterlogging. Since the well had been drilled the previous winter and the site abandoned only three months prior to the visit, slumping was actively occurring. Presumably, the failure reflected low effective stress and low shear strength consequent upon the melt-out of snow mixed with the sump infill material, together with a seepage of water into the sump from adjacent areas.

Panarctic Castel Bay C-68

The well was drilled in the winter of 1975, and is described in a previous report (French, 1976b).

The major concern expressed after the 1975 visit was the possibility that gullying would erode the sump, since the wellsite was located at the foot of a gullied slope with several alluvial fans extending out from the gullies. Inspection in 1976 showed that this was a valid concern; the upslope edge of the sump had been eroded by an ephemeral stream during the spring snowmelt period (Figure 4 b). It must be anticipated that similar erosion will take place each spring since the gully from which the water issued is of significant dimensions and acts as a major collecting area for snow during winter.

It would appear that the problem at this site results from the poor initial location of the sump. A pre-inspection of the site in summer 1974 would have been appropriate.

Elf Kusrhaak D-16

When compared to other wells drilled in the central lowlands of Banks Island, Kusrhaak D-16 is a deep hole (>12,000 feet) and the sump size and volume of waste fluids were probably greater than at other wells.

Fig.4(a) Post-restoration slumping at the Panarctic Elf Bar Harbour E-76 wellsite, northwest Banks Island, July 8, 1976.

Fig.4(b) Gullying and erosion occurring in sump infill material at the Castel Bay C-68 wellsite,July 9, 1976.

Fig. 4(c) Air view of Elf Kusrhaak D-16 wellsite, north central Banks Island, July 10, 1976.

Fig. 4(d) Ground view of standing water body formed along upslope side of the sump, Kusrhaak D-16, July 10, 1976.

This site was also visited previously in 1975 (French, op. cit.). The major environmental and geotechnical concerns identified at that time were (a) the relatively poor compaction of the sump, and (b) the possibility of thermokarst subsidence and gullying, since the site was on a 2-4° slope and underlain by a well developed network of frost fissure polygons formed in silty sands. In addition, the presence of a 40% vegetation cover exerted a distinct influence upon the depth of the active layer. Its absence from the disturbed terrain around the rigsite and on the sump may lead to thermal differences developing between disturbed and undisturbed terrain. For these reasons, the Kusrhaak D-16 site is regarded as one of the more sensitive wellsites on Banks Island.

Observations in 1976 (Figure 4 c) indicate significant changes in the morphology of the sump since 1975. In particular, a standing water body, approximately 50 m long, 10-15 m wide, and approximately 1 m deep had formed along the upslope edge of the main sump (Figure 4 d). In all probability, the water accummulated through (a) subsidence along the sump edge, due to the fact that the overburden was thinnest at that point and (b) the downslope percolation of water through the active layer.

In theory, this water body constitutes a "heat sink" which may induce thermal degradation of the sump overburden. Observations of active thermokarst processes on Banks Island suggest that there are very few instances where water bodies of these dimensions would lead to marked or rapid thermokarst. A further concern expressed in 1975 was the possibility of gullying along the various frost fissures which underlie the site, in a similar manner to those which have developed at the Deminex Orksut 1-44 site on the Big River (French, 1976 b, op. cit.), and at the Gulf Parsons Lake site N-10 in the Mackenzie Delta. Such gullying has not occurred at the Kusrhaak D-16 site and now seems unlikely to occur in the future.

Sample shear strength values indicate greater values in semi-disturbed terrain adjacent to the rig and significantly lower values in the sump infill itself. The latter is undoubtedly the result of winter infilling when frozen materials were used which incorporated significant amounts of snow. However, the localised slumping which had been observed along the downslope edge of the sump in 1975 (French, 1975 c) had stabilized.

In summary, problems at Kusrhaak D-16 relate to sump infilling. When infilled in the late winter of 1974-75 efforts were made to allow for thaw settlement by placing a ridge of excess material along the central axis of the sump. Hindsight suggests that this excess material should have been placed on the upslope edge of the sump where the overburden was thinnest.

Deminex Orksut I-44

This site was visited on July 9, 1976, and again on August 17, 1977 during the IAND Land Use Inspector Training Program. The history of the site and the nature of man-induced thermokarst has been documented earlier (French, 1976 b).

In July 1976, only the site of the summer twin otter airstrip and the disturbed terrain resulting from the infilling of the living quarters' sump were visited. The crude polygonal network of shallow gullies, observed in 1975 and thought to reflect preferential melt along the lines of underlying ice wedges, had further developed into a well defined pattern draining downslope towards the site of the wellhead (Figure 5 a). The hummocky micro-relief of the disturbed borrow pit area had increased to 2.0 m in relative relief and continued to be actively subsiding. Pools of standing water occurred in some of the depressions.

Active layer temperature and thaw depth measurements showed a wide range in the hummocky thermokarst terrain (Table 1). Thaw depths in excess of 95 cm occurred beneath hummocks while depths of less than 50 cm were recorded beneath depressions and standing water bodies. This appears typical of actively developing thermokarst topography (French, op. cit.) since these apparently unusual temperature and thaw depth relationships had also been observed in 1975 (i.e. thermokarst terrain cooler at surface but warmer at depth than adjacent undisturbed terrain).

The summer airstrip showed little signs of thermokarst in spite of the compaction of the surface and the disturbance of the vegetation. Thaw depths were approximately 15 cm greater in the disturbed terrain.

In 1977, the borrow pit topography showed little change from 1976 (Figure 5 b). However, the airstrip had undergone subsidence in a number of places and landing was now marginal for fixed wing aircraft. Depressions as great as 1 m deep had developed in several places and the whole strip possessed an uneven, undulating appearance. Thaw depths measured beneath the airstrip were significantly higher than in adjacent terrain. Also, the airstrip showed signs of dampness not apparent in undisturbed terrain, a phenomenon observed by others elsewhere (e.g. Price, Bliss and Svoboda, 1974).

It is likely that the unusually high summer temperatures experienced on Banks Island in 1977 were responsible for this recent subsidence. At the time of the visit for example, an air temperature of $+17^{o}C$ was recorded. In general, the Western Arctic experienced unusually warm temperatures during the summer of 1977 and this probably induced regional thermokarst activity.

Fig.5(a) Air view of crude polygonal gully network developing at a borrow pit, Deminex Orksut 1-44 wellsite, southern Banks Island, July 10, 1976.

Fig. 5(b) Typical thermokarst topography occurring at Orksut I-44 site, August 16, 1977.

Fig.5(c) Oblique air view of Drake D-68 wellsite, eastern Melville Island, August 7, 1976.

Fig.5(d) Air view of Drake B-44 wellsite, Sabine Peninsula, Melville Island, August 7, 1976.

Terrain problems at Orksut 1-44 relate not to the sump but to thermokarst development in borrow pits and to summer activity around the site in August 1973. The history of the site, since then, clearly indicates the rapidity of thermokarst activity with annual climatic variability.

(ii) Melville Island

Panarctic Drake Point, E-78, D-68, N-67, L-67, K-67

With the exception of K-67, all are capped gas wells, and the area must be regarded as a potential producing field.

All of these wells are located within a highly sensitive, lowland tundra area, possessing a near continuous vegetation cover and underlain by ice-rich and unconsolidated shales of the Christopher Formation. At the time of the visit in August 1976, the sump at D-68 was partially collapsed (Figure 5 c), and ice wedges were exposed in the adjacent terrain. Terrain disturbance in the general area was considerable and, in all probability, resulted from the 1970 blowout and the efforts taken to control it. No evidence of the ice mound which formed at the time (Barnett, 1973) can now be seen.

Of the five wellsites examined, it is significant that only one, D-68, was a deep well (17,766'), and this was the site at which slumping of the sump was observed. The large volume of drilling muds required for D-68 and the associated large sump may be significant factors. Moreover, D-68 was started in June 1973 and completed in March 1974, thus spanning a summer season. All the other wells were completed during their respective winter drilling seasons.

Panarctic B-44

This is a suspended gas well which was drilled to 4,500' in the autumn of 1972. It is located in a wet tundra meadow approximately 200 m from the seashore.

Problems at B-44 do not relate to the sump infilling or to terrain disturbance but to site characteristics. Although the lease is on a gently sloping coastal platform, the wellsite is downslope from an ephemeral stream which originates in rising terrain approximately 300 m inland (Figure 5 d). The sump is currently being eroded by this stream, which may lead to the eventual release of drilling fluids. A summer pre-inspection would have anticipated this problem and required that the well be located approximately 100 m to the south.

Panarctic Hecla F-62; Panarctic Hecla I-69; Panarctic Homestead Hecla J-60

These three wells are located within 10 km of each other and are all very close to the sea on a flat, poorly drained

coastal platform with a continuous cover of mosses, grasses and lichen. Wellsites F-62 and I-69 are capped gas wells and the area is a potential producing field.

Terrain disturbance is evident at all three sites, as well as in the general vicinity. All sumps showed varying degrees of collapse.

The Hecla J-60 is the oldest and also the deepest, being drilled to 11,800' during the summer of 1970. Two summer airstrips can still be recognized in addition to tundra disturbances in the form of vehicle tracks, stream dams and sumps. Aerial inspection revealed three sumps associated with this well. One, located inland (Figure 6 a), has collapsed in the middle and is currently being eroded by a stream which runs directly through the sump towards the sea. The second, nearer the sea, has collapsed in the middle and a small pond has formed at the site. The third, nearest the sea, has collapsed in a semi-circular shape draining to the lower, i.e. seaward, side. There is little doubt that the infilling of these sumps took place before the fluids were sufficiently frozen. In addition, due to melt-out of ice from the infill material during the summer operation, there was a lack of infill material. Finally, the first sump, constructed prior to the spud date was located in a streamcourse.

The Hecla F-62 and I-69 wells are located at the waters' edge. At F-62, the rig sump has slumped and now drains to the sea while the kitchen sump is below sea level; it would seem that this well, when drilled in November 1972, was actually offshore, probably in 3-4' of water. At Hecla I-69, the sump is partially underwater and the seaward end has been completely eroded (Figure 6 b). Several semi-circular slumps, draining to the sea, occur on the landward half of the sump. Since these two wells were shallow (both less than 5,000') and relatively straightforward winter drilling operations (both completed in less than two months), the sumps are not large. At I-69 however, sump fluids escaped during the drilling operation since the sump was clearly of insufficient size to contain the waste effluent.

Long term problems are posed by the locations of these two sumps at the shoreline. First, the slumping of the sumps, and the proximity of seawater indicates that neither is frozen. Second, even if originally frozen, the thermal effects of the seawater may lead to the thawing of the sumps and the release of fluids at some date in the future. Third, ice push and scour, which is particularly effective in the nearshore zone (McDonald and Lewis, 1973) is capable of breaching the sump walls. Moreover, at I-69, ice push ridges are present immediately to the west and testify to the

Fig.6(a) Air view of collapsed sump at Hecla J-60, Sabine Peninsula, eastern Melville Island, August 9, 1976.

Fig.6(b) Air view of sump at Hecla I-69, Sabine Peninsula, August 9, 1976.

Fig.6(c) Air view of Panarctic Chads Creek B-64 well-site, Sabine Peninsula, August 10, 1976.

Fig.6(d) Air view of Panarctic Bent Horn A-02 well-site, August 14, 1976, illustrating terrain disturbance.

importance of this process on exposed headlands, such as at Hecla. Fourth, the long term effects of coastal erosion, although limited to a short period each year, mean that the sumps may be eroded in the future.

Panarctic Chads Creek B-64

This well, located approximately 20 km inland from the coastal Hecla sites, was drilled between December 1974 and June 1975. When visited in August 1976, drilling fluids were seen at the surface and the area surrounding the wellsite had been disturbed (Figure 6 c).

The history of this well illustrates the complexity of the sump problem and the near-inevitability of non-containment of fluids in certain deep exploratory wells. Some of the problems might have been alleviated if the company had acted more swiftly in the appropriate fashion.

A 12,000' deep well was planned, and a sump thought sufficient in size to contain the fluids involved was constructed in December 1974. By the end of drilling in June 1975, the well was over 16,000' deep and the depth of the well had been increased during drilling from 12,000 to 14,000' and ultimately, to 16,000'. In addition, problems encountered down the hole extended the drilling period. By February 1975, the original sump was within 1' of overflowing and in March, the sump overflowed. Bioassay reports on the toxicity of the fluids by Beak Consultants and IAND proved contradictory. In late May, two new sumps were blasted and the frozen sump fluids previously spilt upon the tundra began to melt. In June, the two new sumps were also full and also began to spill waste fluids upon the tundra. These problems were accentuated when the sumps were infilled in the early winter of 1975-76, since the fluids were not adequately frozen. As a consequence, sump fluids were squeezed to the surface and became mixed with the overburden.

Clearly, Chads Creek was not a happy experience for the company and resulted in a critical relationship between the company and IAND officials for some time. From the land use point of view, several lessons can be drawn from the Chads Creek experience.

First, in deep exploratory drilling, the possibility exists that either the geologic formation lies deeper, or is different, than expected, or that technical problems are encountered which extend the drilling period. In either case, a sump constructed to contain fluids from a hole of a predicted depth proves to be too small. For total containment of fluids, either additional sumps have to be constructed or the trucking of fluids to alternate sites has to be considered.

Second, if additional sumps are constructed, additional terrain disturbance will result together with additional costs for the company concerned. The objective should be to minimize both.

Third, the company was at fault in that (a) it did not attempt to anticipate or prevent the original sump from overflowing and only an IAND inspection revealed the situation to IAND officials, and (b) infilling of the sumps was undertaken too early after freeze-up in 1975. The complete disregard for land use regulations and environmental concerns cannot go unnoticed.

In summary, sump problems at Chads Creek reflect both infilling procedures and the difficulties of total containment of fluids within the context of a deep exploratory hole. These problems were compounded by the operating procedures employed by the company concerned. The Chads Creek experience also emphasizes the essential but difficult role which IAND land use inspectors must play in the enforcement of land use regulations in the field.

(iii) Cameron Island

The Bent Horn area of southwest Cameron Island is the site of oil discoveries by Panarctic Oils Ltd. To date, a total of 9 wells have been drilled, of which three are oil producing (N-72, F-72A, A-02). The area will likely become a producing field.

The producing wells are located at the head of the Bent Horn inlet on low lying, gently sloping and well vegetated tundra. This is not typical of the majority of Cameron Island, which consists of moderately dissected and sparsely vegetated semi-polar desert terrain.

A number of factors contribute to the terrain and permafrost conditions at Bent Horn. First, the underlying bedrock is a consolidated sandstone (Trold Fiord Formation) which is relatively resistant to erosion. Second, during the construction of the sumps at I-01 in November 1976, sections in the bedrock were exposed. A well developed network of ice wedges, approximately 5-10 m apart, 2-3 m deep and between 1-2 m wide near the surface, penetrates the frozen bedrock. The size of this polygonal net is considerably less than those developed in unconsolidated material (e.g. as in the Mackenzie Delta) and probably reflects the different thermal contraction properties of sandstone. Third, the sump at I-01 revealed a thin layer of surficial material overlying bedrock. Coarse beach gravels and/or bedrock fragments form a veneer; the whole area is a gently sloping sequence of raised beach materials. Fourth, a thick organic layer composed primarily of moss overlies these surficial materials. Resting directly upon the beach gravels, this organic 'blanket' can be peeled away with a spade. Typically, the organic mat is between 5-15 cm thick.

It provides excellent insulation to the underlying permafrost and contributes to an exceptionally thin active layer in the Bent Horn lowlands. For example, the maximum depth of thaw recorded in August 1977 - an exceptionally hot summer - rarely exceeded 12 cm. A consequence of this shallow active layer is that the top of ice wedges occurs within 15 cm or less of the ground surface. Following vehicle activity and disturbance to the organic layer therefore, these wedges can easily be exposed, thereby initiating gully erosion. Finally, average slope gradients at Bent Horn are low, with slope angles of less than 4^{o} occurring widely. Thus, there is a natural constraint upon the development of gullies, which is further accentuated by the lack of surficial, unconsolidated deposits.

Panarctic Bent Horn A-02

This oil well is located approximately 400 m inland from the head of the Bent Horn inlet on gently sloping well-vegetated tundra. It was drilled in the spring and summer of 1976 to a depth of nearly 10,000'.

When the site was examined in August 1976, terrain disturbance had occurred over much of the lease area (Figure 6 d). The surface organic mat had been disturbed over a wide area following vehicle movement. In places, ice wedges were exposed in vehicle tracks and gullying along ice wedges in the sump wall adjacent to the rig was threatening to undermine the rigpad. Around the site, mattings and catwalks were being laid down to facilitate movement and access to the lease was by helicopter only.

Restoration took place during the winter of 1976-77. The sump was infilled and the whole site smoothed and backbladed. The surface organic mat, although disturbed and killed during the summer, had remained on the site and was redistributed over the lease. The gullies were infilled and buried during the restoration.

When the site was revisited in August 1977, little serious thermokarst or gullying had developed. The veneer of redistributed organic material, acting as a mulch, had limited thawing during the summer. This is all the more significant since the 1977 summer was exceptionally warm. It must be concluded that the unique topographic and vegetation conditions of the Bent Horn area (i.e. low topographic gradients, excellent thermal properties of the organic layer, lack of unconsolidated materials, etc.) had acted to prevent serious long term terrain damage.

Questions must be raised however, concerning the extent of the terrain disturbances made in 1976 and the wisdom of summer operations in such well vegetated lowland tundra regions. The lack of aggregate, for pad and road construction, on both

Cameron and Melville Islands, is particularly relevant to any assessment of the impact of summer drilling. If such aggregate were available, terrain damage might be significantly reduced.

In summary, problems at Bent Horn A-02 relate not to the sump but to terrain disturbances associated with summer operations. It is clear that summer drilling in such well vegetated areas of the high Arctic should only be sanctioned if there is close control over vehicle movement. Preliminary indications at Bent Horn are, however, that restoration has been largely successful. At the A-02 site, the main problem, that of a large area of dead, blackened and disturbed tundra, is mainly an aesthetic one.

Panarctic Bent Horn I-01

This well, completed during the 1976-77 winter drilling season, is located on essentially similar terrain to the A-02 wellsite. The sump has been instrumented as part of the ALUR sump monitoring program (see French and Smith, ALUR Sump Studies 2, in press).

In contrast to A-02, sump problems were encountered at this well. These problems can best be explained in terms of the complex geology of the Bent Horn area.

Faulting of the Devonian limestone reef formations in the Bent Horn area has resulted in the localising of oil into small pockets rather than into one, simple, well defined reservoir. Based primarily upon the results from the Bent Horn A-02 well, approximately 2 km distant, the I-01 well was planned as a step-out well, approximately 10,000' deep. However, drilling did not reveal the expected structures and the depth of the hole was increased beyond 12,000'. Then, deviation from the target area necessitated directional drilling for a further 5,000'. Thus, the I-01 well turned out to be considerably deeper than the A-02 well and the initial sump proved to be completely inadequate to contain the additional fluids involved in deeper drilling. A second sump was constructed some distance from the rig and frozen fluids were removed periodically from the main sump and transported to the new sump.

Infilling of the sumps took place in late spring of 1977. When inspected in August 1977, the first sump was waterlogged and drilling fluids were present at the surface of the main sump (Figure 7 a). In all probability, the sump had been too full when infilling took place and frozen fluids probably became mixed with the sump infill material. A lack of easily accessible gravel, with which to form a cap over the sump, was a further problem.

Fig.7(a) View of main sump at Bent Horn I-01, August 10, 1977, approximately 5 months after sump infilling.

Fig.7(b) Air view of restored sump at Elf Dyer Bay I-59 wellsite, Prince Patrick Island, August 16-17, 1976.

Fig.7(c) Air view of Shell Niglintgak M-19 wellsite, September 10, 1976.

Fig.7(d) Air view of Imperial Taglu F-43 wellsite, Mackenzie Delta, September 9, 1976.

The amount of terrain disturbance around the I-01 site, apart from that associated with the construction of the two sumps, is not excessive and is less than that associated with the A-02 site. Without doubt, this reflects the advantages of winter drilling.

(iv) Ellef Ringnes Island; Panarctic et al Sirius K-28; Panarctic Mocklin Point D-23

These sites were visited in August 1976. Sirius K-28 is situated on a shallow interfluve located on flat, monotonous terrain underlain by sand and gravel of the Beaufort Formation. Vegetation is virtually absent except for certain isolated cushion plants, and there is no evidence for high ice contents in the underlying materials. The area is typical of polar desert terrain developed upon Beaufort materials. At Mocklin Point D-23, the well is located upon a flat alluvial sand plain, or sandur, processing a desert 'armour' of gabbro, quartzite and sandstone pebbles.

At both sites, the sumps present no problems; there was no slumping and subsidence of the sump overburden and no obvious release of drilling fluids. The absence of sump problems at both sites is interesting since Sirius was a winter operation, drilled between November 1973 and March 1974, while Mocklin Point was a summer operation, drilled in 1975. In the case of Mocklin Point, the sump was open during the summer and not infilled until the winter of 1975-76. These observations suggest that in the very arid and sparsely vegetated polar desert environments of the high Arctic, the impact of summer and winter drilling operations is nearly the same. Moreover, with reference to sumps, the virtual absence of vegetation and wildlife means that spillage of toxic drilling fluids is not so critical as in other areas further south. At the same time, the relative lack of ground ice, as compared to parts of Banks Island and the Mackenzie Delta, suggests that sump construction and thermokarst problems are not so important.

Amund Ringnes Island; Panarctic Amund Central Dome H-40; Panarctic Gulf West Amund 1-44

These sites were visited in August 1976. Both were winter operations, H-40 being drilled in 1970-71 and 1-44 in 1971-72. West Amund 1-44 is located in a shallow creek bed which, at the time of the visit, was dry. The general area was a sandy outwash or sandur surface. No slumping, subsidence, or seepage of fluids was noticed. At H-40, some slumping of the sump had occurred but it was not possible to land to ascertain the reason for this.

Prince Patrick Island; Elf Dyer Bay I-59; Elf Wilkie Point J-51

These two sites were visited in August 1976. No sump problems were observed at either (Figure 7 b). Both wells were drilled in winter and both are located on sand and gravel, I-59 underlain by Beaufort Formation and J-51 by Wilkie Point Formation sandstone. Both sites are typical of true polar desert environments. Temperatures measured in the active layer at these sites illustrate how drilling operations in such areas pose minimal environmental or terrain problems. There was little difference between disturbed and undisturbed terrain (Table 2). In general, the observations made on Ellef Ringnes and Amund Ringnes Islands support this view.

2. Mackenzie Delta

The Mackenzie Delta represents a unique Arctic environment. The treeline passes through the southern part of the area and the terrain consists of innumerable lakes, ponds and drainage channels. For the most part, the underlying sediments are ice-rich silt and sand of Recent age. The area is of considerable ecological and biologic importance and is an important trapping and fishing locality for residents of Aklavik and, to a lesser extent, Inuvik and Tuktoyaktuk.

Summer temperatures in the Mackenzie Delta are considerably warmer than those of the western Arctic Islands with July maxima often exceeding $+20^{\circ}C$, particularly inland. As a result, active layer thicknesses in excess of 1.5 m may occur on well drained, poorly vegetated, sandy locations. Such situations are rare however, since a relatively luxurious shrub tundra vegetation is widespread north of the treeline. South of the treeline, black spruce, birch, alder and willow predominate. This vegetation cover, combined with poor drainage, results in much shallower active layers, usually between 30-60 cm. The high summer temperatures, the important thermal role of the vegetation, and the ice-rich and unconsolidated nature of much of the underlying sediment make the Mackenzie Delta area particularly sensitive to disturbance and thermokarst development. Various terrain sensitivity and surficial geology maps for the Delta area north of the treeline are available (Rampton, 1972, 1974; Eyk and Zoltai, 1975).

The Mackenzie Delta can be divided into a number of different regions and sub-regions on the basis of terrain and permafrost condition (Mackay, 1963). In this study, three areas are distinguished (Figure 3).

(i) The Modern Delta, which can be subdivided into:

(a) north of Reindeer Channel and between the East and Middle Channels. This area is low lying, poorly drained, tundra underlain by ice-rich alluvial silts and subject to annual flooding;

(b) south of the treeline, between the Caribou Hills on the East and the Richardson Mountains on the west. The area consists of numerous lakes separated by narrow divides from winding, single channel stream networks. Forest and forest-tundra vegetation is typical.

(ii) The Pleistocene Delta, north and east of the Caribou Hills, consisting of gently undulating, relatively well drained topography with numerous thermokarst lake basins and pingos, and underlain by ice-rich silt, sand and, in places, gravel.

(iii) Upland Terrain, flanking the east slope of the Richardson Mountains on the west of the Delta, and the Caribou Hills extending north from Inuvik on the east side of the Delta. Both areas are transitional between forest and tundra.

Each of these environments necessitates a slightly different evaluation of terrain sensitivity conditions and land use procedures.

(i) The Modern Delta

Shell Niglintgak B-19, M-19, H-30

All these wells are located in flat low lying areas of the flood plain of the modern Mackenzie River.

Sump problems at all sites relate to a lack of infill material (Figure 7 c). This reflects the very high ice content of the underlying silts and the melt-out and volume loss which occurs during summer. The most apparent material deficiencies occur at Niglintgak M-19, a late summer/early winter operation drilled between June 1974 and January 1975, and Niglintgak H-30, where the sump remained open during the summer of 1973.

Typically, the restored sump at each locality consists of a shallow depression which traps water each spring as the floodwaters subside. These water bodies may generate a 'heat sink' effect and lead to thawing of the sump overburden. In addition, they may become polluted and pose a threat to wildlife. Since these localities are all close to a major channel of the Mackenzie River, and subject to annual flooding, consideration ought to be given to the disposal of fluids into this channel or directly upon tundra, relying upon dilution and the spring flood to disperse them.

Imperial Taglu D-55, F-43

Sump problems in the Taglu area appear essentially similar to those in the Niglintgak area and are illustrated by Taglu D-55 and Taglu F-43 (Figure 7 d).

At Taglu D-55, the sump had collapsed around the edges. This well had been drilled between April and July 1972 and the sump had been left open that summer. As a consequence, melt-out of ice from the infill material had occurred resulting in a loss in volume, and degradation and enlargement of the sump probably had occurred also. In spite of substantial amounts of gravel placed over the sump, subsidence occurred along the edges where the gravel cap was thinnest and where, presumably, continued thaw of the sump wall had continued during the following year.

(Proposed) Shell Tullugak K-31

This site illustrates some of the difficulties of operating in the flood plain area of the Mackenzie Delta. The location was an extremely wet, low lying flood plain of one of the major channels of the Mackenzie River (Figure 8 a). Overland movement of any sort in summer was impossible. As a result, the site was prepared in the winter of 1975-76 for drilling during the following winter. A sump was constructed in March 1976 and an ice-cored dyke was constructed around the sump. Urethane matting was installed as a 'liner' to the sump to prevent thawing over the summer. A drilling and living quarters' platform, connected by a catwalk, was also constructed upon piles, approximately 4' above the ground surface.

The spring flood of 1976 was higher than usual and completely covered the site. At one point the drilling platform was covered with 4' of water. The dyke around the sump was of insufficient height and the sump became infilled with water. In July, after water levels had fallen, the sump was pumped out but subsidence and slumping of the sump had already begun since the insulation matting had been disrupted. Because a new sump would be required and because this could only be constructed in mid or late winter when ice thicknesses were sufficient to allow movement of heavy equipment along ice roads, it was not possible to complete the well during the 1976-77 winter drilling season. Accordingly, the company abandoned the site.

The Tullugak experience clearly demonstrates the hazards of operating in the flood plain areas and, more important, the short time period during which a company can undertake construction involving heavy equipment. In this case, the very wet site ruled out summer operations; at the same time, equipment cannot be stored at the site for activation immediately following freeze-up because of the spring flood. Furthermore, the

Fig.8(a) Air view of proposed Tullugak wellsite, Mackenzie Delta, September 10, 1976.

Fig.8(b) Air view of Gulf Parsons Lake N-10 well-site, Mackenzie Delta, September 10, 1976.

Fig.8(c) Air view of Gulf Parsons Lake A-44 wellsite, Mackenzie Delta, September 10, 1976.

Fig.8(d) Air view of Shell Beaverhouse Creek H-13 wellsite, on sloping upland terrain on west side of Mackenzie Delta, September 8, 1976.

movement of heavy equipment along winter ice roads is not usually possible until November or early December and cessation of activities must occur in mid April to anticipate thaw and the break-up of river ice. Therefore, a drilling operation which, in other environments, might be started and completed in one winter drilling season may require two winters for completion in the flood plain areas, with an open sump for at least one summer.

Under such conditions, drilling without a sump may be a partial solution to these logistical and scheduling problems, since fluids deposited on the surface during winter drilling would be removed and diluted by the spring flood.

(ii) The Pleistocene Delta

In contrast to the Modern Mackenzie Delta, the Pleistocene Delta is composed of undulating, sometimes hilly, terrain. There are numerous lakes, drained lake basins, and pingos. The area is not subject to annual flooding. The underlying silt, sand and gravel is ice-rich with massive icy bodies, several meters thick, occurring widely. As a consequence, the problems of sump construction and thermal melt-out in these areas are of importance.

Parsons Lake Area

The Parsons Lake area contains a number of capped gas wells and is likely to become a producing field in the future.

Problems relating to sumps in the Parsons Lake area are (a) the high ice contents of many of the underlying materials, which become exposed in sump walls and, if left open during the summer, lead to substantial enlargement of the sump, and (b) hilly topography and the presence of numerous lakes which makes the location and excavation of large sumps difficult.

Gulf Parsons Lake N-10

The actual site of the well was on sloping terrain, surrounded by lakes on three sides (Figure 8 b). The immediate area surrounding the wellsite consists of a shallow depression occupied by ice wedge polygons. A thick peat and/or organic layer extends downslope towards the lake to the east. The sump was constructed in January 1973 on a 2-4% southeast facing slope. IAND files record the history of a sump problem at this site.

On May 13, 1973, fluids were reported leaking beneath a dyke constructed at the lower southeast corner of the sump and entering a nearby lake. Several samples of the fluids were found to be toxic to fish upon analysis. The sump was left

open during the summer. In July, further leaking from the sump occurred, causing considerable gullying along the ice wedges on the slope leading towards the lake.

Central to this situation was the small size of the initial sump and the efforts made by the company to increase the sump at a later stage. The hilly nature of the site precluded the possibility of sump construction on level ground. Thus, the fluids quickly exceeded the 4' freeboard at the lower end of the sump while the upper end remained empty. Furthermore, the ice-rich nature of the underlying sediments and the possibility of thermal erosion and sump instability necessitated the location of the sump away from the surrounding water bodies. In April 1973, when it was realized that the sump was too small, the company pushed sump infill material out of the sump to form a dyke at the lower southeast corner, thus increasing the sump dimensions by approximately 50'. However, this dyke was constructed over approximately 2-3' of snow which had fallen that winter. In May, as temperatures rose above freezing, this snow thawed and allowed the escape of fluids beneath the dyke. This thaw was probably accelerated by the temperature of the drilling effluent in the sump which may have been 90-120^{o}F at time of deposition. Then, in July, the thawing of ice wedges exposed in the side of the sump enabled the further escape of fluids. Terrain damage was considerable; according to industry consultants, gullies 2-3 m deep developed along the ice wedges downslope from the sump. They were arrested only after the placement of thick sods of peat to act as insulation.

It might be argued that, on account of the topographic and permafrost conditions at the site, the Parsons Lake N-10 well might best have been drilled without a sump.

When visited in 1976, the Parsons N-10 site showed a fair degree of recovery. The gullies eroded by the escaping sump fluids in 1973 had stabilised and natural revegetation was occurring rapidly. No further sump problems were apparent.

In summary, the Parsons Lake N-10 site illustrates the importance of topographic and permafrost controls in determining the suitability for an operation with a sump, and emphasizes the necessity to consider alternate methods of disposal and containment of drilling fluids. Finally, a pre-inspection and soil testing program the previous summer would have indicated the nature of the problems ultimately encountered, and they might even have been avoided.

Gulf Parsons Lake A-44

At the Parsons Lake A-44 wellsite (Figure 8 c), IAND records indicate that the lower half of the sump was excavated in massive ice. Moreover, drilling continued throughout the

summer of 1976 and the sump walls experienced considerable melt-out leading to an enlargement of the sump by late summer. When visited in 1976 the sump was capped with a large mound of gravel, approximately 6 m high, and a revegetation program had been initiated. No signs of subsidence, collapse or leakage were apparent. However, IAND files indicate that problems were encountered when infilling of the sump took place in February 1976. During backfilling, the sump 'broke' and fluids squeezed to the surface and became trapped at a level above the surrounding ground (the 'volcano' effect). It was decided to allow these fluids to flow out of the sump under gravity and to freeze in a containment dyke, specially constructed for that purpose. These frozen fluids were then trucked to other sumps in the vicinity. Substantial amounts of gravel were then moved to the site and used to complete the backfilling.

The reasons for the break in the A-44 sump may be related to its eventual large size, which would militate against complete freezing during the following winter.

Gulf Parsons Lake D-20

The release of drilling fluids following site restoration has also been encountered in the nearby Parsons Lake D-20 wellsite. This well was drilled in 1975-76 and restored in 1976-77. The sump was constructed at the top of a south facing slope draining towards Parsons Lake. A sizeable gravel cap was placed over the sump. By the end of the first summer after restoration, in September 1977, fluids were seen to be seeping to the ground surface, approximately 30 m from the southwest corner of the sump and draining towards Parsons Lake. IAND records indicate that a thick 4' ice lens was encountered in the sump wall during construction. This suggests that melt-out along the lens has allowed the sump fluids to escape under a hydrostatic head induced by the weight of the gravel pad. When visited in March 1978, a small icing mound, approximately 1 m high and 3 m in diameter had formed at the site of the seepage.

Imperial Wagnark G-12

This well was drilled during the summer of 1973. IAND files indicate the sump was constructed in ice-rich gravel and sand. Presumably, since this was a summer operation, thawing and enlargement of the sump must have occurred during the summer and the company must have been faced with a lack of infill material the following winter. In response, gravel was hauled to the site and a substantial cap was constructed.

When visited in 1976, no signs of subsidence or collapse of the gravel pad were apparent and terrain disturbance in the surrounding area was minimal.

However, the general siting of this well was not good. It had been located in a shallow wet depression in which ice wedges and peaty, organic materials were present. A gravel access road and a pad beneath the sites of both rig and living quarters' were the reasons why relatively little terrain disturbance had occurred. In summary, the use of substantial quantities of gravel appears to have been critical in minimizing a number of potential problems.

(iii) Upland Terrain

Shell Beaverhouse Creek H-13

This well was drilled in the winter of 1970-71. It is located on a sloping (3-5°) upland tundra surface on the foothills of the Richardson Mountains. The slump has collapsed along the downslope edge (Figure 8 d). In addition, the site was a shallow wet depression used as a seepage line. Revegetation around the site was good however, and apart from the sump, site restoration appeared successful.

The failure of the sump infill appears partially related to poor infilling technique at the time of restoration in the late winter of 1970-71. Not enough material was located on the downslope side of the sump. Probably most important, however, the seepage of water downslope in summer induced saturation of the sump infill, reducing the shear strength and thereby promoting failure.

3. Alaskan North Slope

The Alaskan North Slope is a natural extension westwards of the low Arctic tundra of the Yukon coastal plain and the Mackenzie Delta. However, a complete analogy with Canadian conditions is not possible since high Arctic tundra and true polar desert terrain is lacking.

There are two areas of oil and gas exploration activity:

(a) the Prudhoe Bay area, the site of one of the largest oil fields discovered in recent years in the Arctic, and;

(b) the United States National Petroleum Reserve Number 4, (NPR-4) located west of the Colville River and to the south of Point Barrow.

This section of the report presents observations made during a visit to NPR-4 in June 1977. The location of NPR-4 and the sites visited are presented in Figure 9 and Appendix II.

(i) Objectives

The objectives were (1) to examine terrain conditions and revegetation adjacent to old wells drilled without sumps in

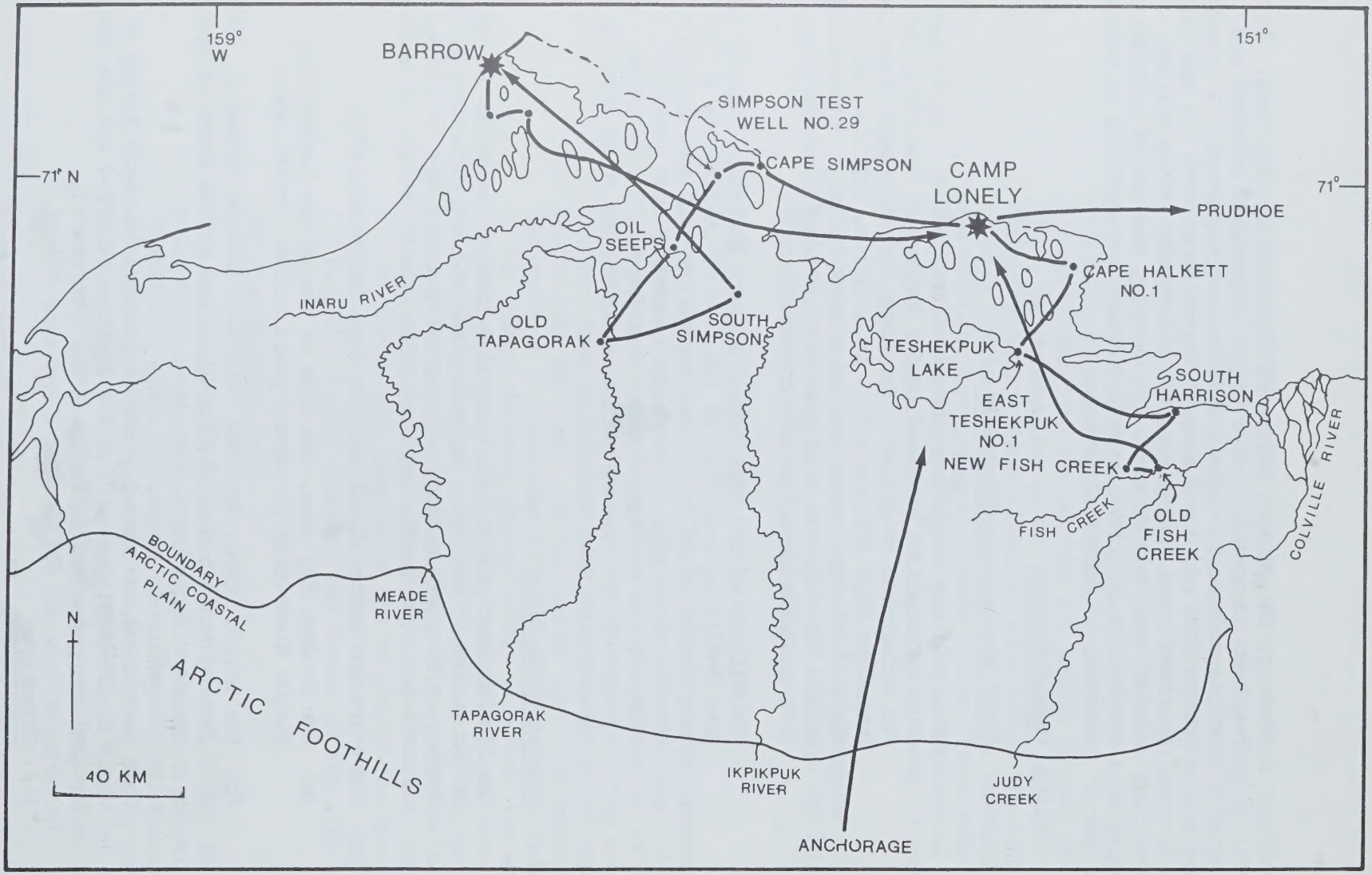

Fig. 9. Traverses made in NPR-4, Alaska, June 28-30, 1977

the late nineteen forties and early fifties when the Reserve was under naval control, and (2) to visit more recent well-sites drilled by Husky Oil (NPR) Operations Ltd., under contract to the United States Geological Survey.

The relevance of these early Alaskan experiences to the ALUR sump project is obvious since such sites might provide an insight into the environmental impact and speed of site recovery at locations drilled either without sumps or where non-containment of fluids occurred. Moreover, the opportunity to examine modern U.S. drilling operations enables comparison with Canadian procedures.

An account of the early drilling activities in NPR-4 between 1944-53 is available in Reed (1958). A very comprehensive and up-to-date environmental impact statement of recent drilling in NPR-4 has recently been made available (U.S. Navy, 1977).

Permafrost and terrain studies, aimed at the documentation of terrain disturbance and general site recovery at old wellsites were commenced in 1977 by Dr. J. Brown, of the U.S. Army Cold Regions Research and Engineering Laboratories (CRREL), Hanover, New Hampshire (Brown, 1977).

(ii) Old Wells, NPR-4

One of the earliest wells drilled in the Reserve,the Simpson Test Well No. 29 (Figure 10 a), was completed in 1949 without the use of a sump. When visited in 1977, substantial quantities of unused drilling muds remained at the site, together with remnants of the old rigpad and the wooden pilings used. In general, the same degree of site recovery and clean-up occurs at the other old wellsites visited, notably Simpson Test Well No. 1, Old Tapagoruk, and Old Fish Creek.

The Old Fish Creek wellsite, drilled during the summer of 1949, is probably the worst of these early sites as regards terrain disturbance and site recovery. Substantial thermokarst subsidence had occurred along vehicle tracks and in the adjacent area. Debris, in the form of pilings, raised catwalks, and gas drums litter the surrounding area (Figure 10 b). Currently, Husky Oils is undertaking a clean-up program in the Reserve. Revegetation and thermokarst studies are being undertaken at Old Fish Creek by CRREL (Brown, 1977).

An overall assessment of these sites suggests that the absence of sumps and the spilling of drilling muds directly upon tundra has not resulted in any obvious long term environmental damage. In areas adjacent to the old rig, regrowth is sometimes more prolific than in adjacent undisturbed terrain. Typically, Calamogrostis and Poa grasses have colonised the disturbed areas. If the aesthetic, terrain disturbance and debris

Fig.10(a) Air view of Simpson Test Well No. 29, U.S. National Petroleum Reserve (NPR-4), Alaska, showing old rig pad and waste drilling muds, June 28, 1977.

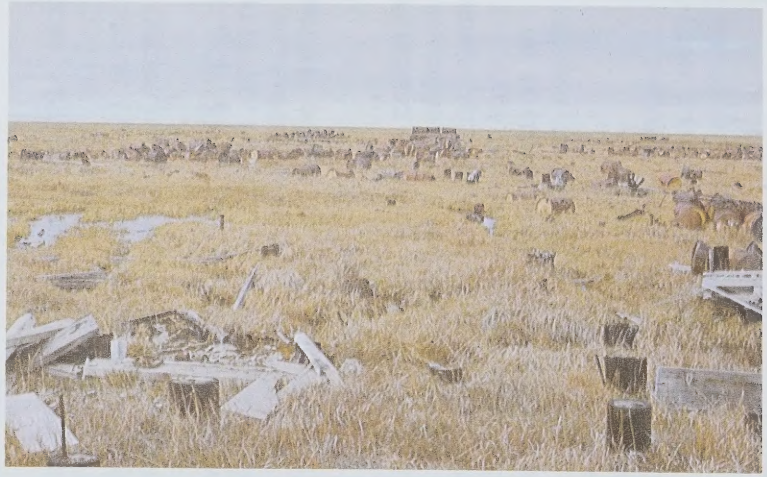

Fig.10(b) Debris at the Old Fish Creek wellsite, U.S. National Petroleum Reserve, (NPR-4), Alaska, June 30, 1977.

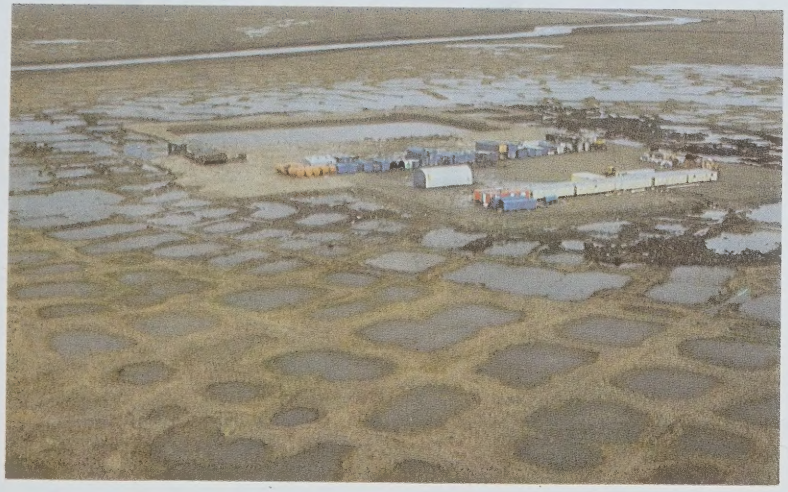

Fig.10(c) Air view of Husky Oils (NPR) Operations Ltd., South Simpson Wellsite, NPR-4, drilled in 1976-77, June 30, 1977.

Fig.10(d) Air view of a multiple well drilling operation at Prudhoe Bay, Alaska, using large gravel pads and communal sump, June 30, 1977.

related problems are excluded, one must conclude that the drilling of these early wells without sumps has not been excessively harmful. In fact, the degree of natural site restoration is remarkably high. Furthermore, the natural occurrence of beaded drainage and thermokarst pools on the adjacent tundra, and the trenching which has occurred along vehicle tracks, suggests that sumps constructed in this ice-rich terrain would have experienced severe melt-out problems in summer.

There are several differences between these early Alaskan operations and current drilling practices in Canada. For example, since these early wells rarely exceeded 4,000', the need for large volumes of drilling fluids and, in particular, the addition of heavy metals to contain the high formation pressures at depth, did not arise. In all probability, the drilling fluids used were simple starch-based muds. Thus, the absence of sumps did not reflect a negative attitude towards sump effectiveness but rather, different operating conditions. Furthermore, the volume of sump fluids probably did not justify the costs of sump construction. These comments indicate, therefore, that the degree of site restoration seen at these old sites may not necessarily indicate what will happen if sumps are not used in Canadian operations.

(iii) Modern Wells, NPR-4

Wells are currently being drilled in both NPR-4 and at Prudhoe Bay. All of these modern operations use sumps (Figures 10 c, d). However, these are small by Canadian standards. For example, at the Husky South Harrison wellsite, drilled in 1976 to a depth of 12,000', the sump was little more than 6' deep and 100' x 150' in dimensions.

According to Husky officials, sumps are used in current drilling because the wells are intermediate or deep, and the volume of fluids involved is considerable. The policy of total containment, while accepted, is not the major consideration. Instead, the sump is regarded primarily as a blowout/safety procedure (i.e. a place to deposit excess fluids if problems develop). Non-containment of fluids is not regarded as a problem; only at one site - Teschepuk Lake - were sump problems given significant mention. In this case, a small amount of fluid had breached the dyke and entered Teschepuk Lake.

Modern drilling usually takes place in flat, poorly drained tundra, dominated by low centred ice wedge polygons and thermokarst lakes. To minimize terrain disturbance, the generous use of gravel and the restriction of the operation to a small geographic area are procedures widely adopted. An abundance of gravel aggregate is a distinct advantage which Alaska possesses over many parts of the Canadian Arctic.

No modern sites were examined where site restoration has been completed. According to Husky officials, sumps are infilled in both winter and summer, the latter often preferred. In some cases, material used for the rigpad is pushed into the sump. Little or no doming of material is attempted. Sand is often preferred to gravel for pad construction since (a) it can be blown into a 'natural' form quickly by wind, and (b) it promotes revegetation better than gravel which is excessively well drained. Sands, of either fluvial or eolian (i.e. dune) origin are hauled to the wellsites during winter.

(iv) Discussion: The Alaskan Experience

The following comments arise from an assessment of Alaskan drilling experience:

(1) Despite the absence of sumps, the drilling of old wells in NPR-4 does not appear to have had an impact upon the adjacent vegetation. After 25 years, revegetation is well advanced and, in some cases, growth is more prolific than adjacent undisturbed terrain.

(2) The experience of this early Alaskan drilling may not necessarily be typical of what might happen at Canadian sites if drilling were undertaken without a sump. Drilling conditions in modern Canadian wells are different, notably (i) wells are often deeper and require greater volumes of fluid, and (ii) drilling fluids are more complex in chemical composition.

(3) Sumps currently being used for intermediate or deep wells on the Alaskan North Slope appear significantly smaller than those constructed for similar wells in Canada. The majority of the sump is constructed above ground, contained by a dyke.

(4) The relative success of modern Alaskan drilling, as regards site restoration and terrain disturbance, rests upon two critical factors: (i) the presence of easily accessible aggregate sources for use in the rigpad and for sump infilling, (ii) the relatively shallow depth of much Alaskan drilling and the relatively straightforward nature of the subsurface geology has meant that technical problems and/or extensions to the drilling period are not common.

(5) The current trend towards deeper exploratory drilling in NPR-4 suggests that Alaskan sump problems may increase in the future.

IV. CONCLUSIONS

General

1. Sites visited in Northern Canada in 1976 and 1977 are thought to be a representative sample of wells drilled north of the treeline, as regards age, site and operating conditions.

2. Environmental conditions vary widely north of the treeline. It is necessary to distinguish between (a) low Arctic tundra (e.g. Mackenzie Delta), (b) high Arctic tundra (e.g. Banks Island, Southwest Cameron Island), and (c) polar desert regions (e.g. Prince Patrick Island). Significant differences are related to duration and magnitude of summer thaw, vegetation cover, ground ice conditions, underlying geology (bedrock and surficial), and accessibility to aggregate sources.

3. Certain areas experience naturally occurring critical or hazardous conditions, notable examples being the annual flooding in parts of the Modern Mackenzie Delta, and detachment failures in terrain underlain by Christopher Shales. In addition, some areas are critical in terms of plant life and animal distributions and movement.

4. Operating conditions attached to Land Use Permits must take into account these different environmental conditions. Assessments of site conditions must be considered within its regional context. Furthermore, assessment at a locality must consider the likelihood of further wells being drilled in that area.

Specific

5. Approximately 25-30% of the wellsites visited experienced problems of varying magnitudes related either directly or indirectly to the sump and/or the containment/non-containment of waste drilling fluids.

6. No trend was discernible as to whether sump problems had increased or decreased during the period 1970-77. However, bearing in mind the increased awareness of Land Use Inspectors, and industry operators in recent years, sump problems actually may have decreased over this period. More important than age in determining sump problems are general site conditions and the timing and nature of the drilling operation.

7. An analysis of sump problems is presented in Table 3. Basically, problems can be of three types: Type A - non-containment problems during drilling; Type B - melt-out problems during summer operations; Type C - restoration problems which may occur either during restoration or subsequent years.

8. Specific examples of Type A problems include Bent Horn 1-01, Chads Creek B-64 and Parsons Lake N-10. Non-containment can

be the result of either too small a sump for a given operation or a given operation assuming larger dimensions (e.g. deeper drilling) than planned. As such, Type A problems are the result of either bad planning in initial sump construction or drilling problems. In the case of the former, IAND should ensure that sump sizes as specified in Land Use Permits be adherred to; in the case of the latter, the company concerned has an obligation to discuss remedial measures with IAND officials as soon as it is realized that the drilling program is not progressing as scheduled.

9. Remedial measures for Type A problems include (a) the construction of additional sumps, (b) the trucking of fluids to other disposal sites, (c) the modification of the existing sump. Experience from Chads Creek and Bent Horn indicate that the construction of additional sumps results in considerable terrain disturbance and, almost inevitably, a mixing of sump fluids with overburden, or a scattering of frozen sump fluids upon the tundra. In areas where several wells are being drilled, the trucking of fluids in winter to other sumps might be considered, or to a central sump constructed in an area approved by IAND. Parsons Lake N-10 illustrates the difficulties of extending and modifying a sump already in use.

10. Type B problems occur during a summer operation or when a sump is left open during a summer. They commonly take the form of degradation of sump walls particularly along ice wedges leading to the undermining of the rig structure and/or the escape of fluids.

11. Remedial measures include the placing of urethane matting and other insulation upon the sump walls, and the diversion of rigwash.

12. Type C problems are related to sump restoration and were the most common sump problems encountered. At least six problems can be recognized:

    (a) The 'volcano' effect - occurs during sump infilling when sump fluids are not completely frozen and the surface breaks under the weight of the overburden, allowing fluids to squeeze to the surface.

    (b) Sump subsidence and collapse - usually occurs during the summer following restoration. Reflects the incorporation of snow/ice in the infill and/or seepage of water downslope into the sump in summer.

    (c) Lack of infill - results from melt-out of ice during summer in the sump infill material. The subsequent depression promotes a standing water body over sump which serves as a heat sink. This problem is particularly acute in areas where there is a lack of accessible aggregate.

(d) Leakage of fluids - occurs if ice lenses in sump wall melt out or if the sump is too full upon infilling leading to seepage through the seasonally thawed zone.

(e) Poor geographic locations - for example, where sumps are located in water courses, etc.

(f) Excessive terrain disturbance - occurs in summer operations in well vegetated ice-rich tundra and/or where additional sumps were constructed and/or where technical drilling problems were encountered.

13. Remedial measures for Type C problems must take into account the overall benefits of such action, since remedial action after the site has been abandoned is both costly and likely to induce further terrain damage.

14. Waterlogging and sump subsidence is one of the most frequently occurring of the Type C problems. This is the result of either (a) excessive snow and ice being incorporated in the sump infill or (b) a location on a slope where seepage during the summer causes the build up of pore water pressure in the overburden. The removal of snow from the sump before infill, careful infilling to minimize the snow pushed into the sump, and the construction of drainage lines upslope of the sump to divert seepage are remedial measures.

15. The placing of large domed gravel caps on sumps in the Mackenzie Delta is a standard procedure which seems to work well to counter slumping, loss of infill, or 'volcano' problems. Gravel aggregate is limited in quantity and thus expensive to obtain in parts of the high Arctic. Remedial procedures adopted for the Mackenzie Delta may therefore be unrealistic in this region.

16. A pre-inspection during summer together with air photo analysis ought to be a requirement for any permit. Such a procedure would have solved a number of problems related to poor geographic locations.

17. The use of gravel to alleviate lack of infill and counter 'volcano' effects during sump infilling are standard procedures which work reasonably well for some companies in the Mackenzie Delta. Modern Alaskan experience illustrates the effectiveness of gravel pads in reducing terrain disturbance, particularly in summer operations. The use of gravel, if available, at Canadian sites may reduce terrain disturbance and sump problems.

18. The relationship between the occurrence of sump problems and various drilling schedules is analysed in Table 4. Drilling operations in Arctic Canada can be grouped into one of three time frames:

(a) One season winter drilling;

(b) Two season winter drilling (i.e. sump left open during summer and restoration in second winter) or

(c) One Season summer drilling.

19. There is no doubt that the least sump problems occur in a one season winter drilling program, in which commencement and restoration are completed during the winter months. Typical problems which occur are Type A problems or certain of the Type C problems, notably poor geographic locations or bad infilling around the sump edges and summer subsidence of the overburden.

20. Two season winter drilling poses more problems than one season drilling on account of the fact that such an operation is usually a deep hole or has become extended for one reason or another, thus continuing into the summer season. As a consequence the sump is left open, the sump may become inadequate in size, and remedial measures for Type B problems would not have been undertaken. Finally, infilling the following winter after substantial Type B problems would lead to a variety of Type C problems, notably the 'volcano' effect and/or a lack of infill.

21. Summer drilling has the highest probability of occurrence of sump problems, based upon the sites visited in 1976 and 1977. In addition to Type A problems, Type B and Type C problems are clearly relevant.

22. There are two localities where sump problems might have been avoided if alternate methods of disposing of drilling fluids had been employed.

(a) Modern Mackenzie Delta - In sensitive ice-rich and well vegetated tundra subject to annual flooding, direct spillage or deposition of fluids in major channels may be more appropriate.

(b) Coastal locations - where a well is located near shore or offshore, dilution and dispersion of fluids may be more appropriate.

In both cases, dilution effects will probably negate any toxicity effects.

23. In contrast to tundra environments few sump problems were encountered at wells drilled in the polar desert environments of the high Arctic. In general, one must regard polar desert environments as less sensitive to terrain and sump problems on

account of the lack of vegetation, the general aridity of these areas, and the relative lack of ground ice. At the same time, the necessity for containment of fluids may not be of such high priority since wildlife and human habitation of such regions is limited.

DEPTH (cm)	THERMOKARST TERRAIN HUMMOCKS	THERMOKARST TERRAIN DEPRESSIONS	SUMMER AIRSTRIP (compacted)	UNDISTURBED DRYAS TUNDRA
Surface*	10.0	9.5	11.0	14.0
10	8.0	5.0	8.5	8.0
20	6.0	3.0	6.0	5.0
30	5.0	2.0	5.0	3.5
40	4.5	0.5	2.5	2.5
50	4.0			
60	3.0			
FROST TABLE 9/7/76	>80cm	57cm	60-70cm	60cm
SHEAR STRENGTH**	0.16-0.70kg/cm^2		0.5-0.9kg/cm^2	0.4-0.6kg/cm^2

*Temperatures taken with YSI thermistor probe and telethermometer.

**Readings taken with Soiltest Hand Vane Tester.

TABLE 1. Active layer temperature (°C), thaw depth and shear strength values at Deminex Orksut 1-44 wellsite, Banks Island, July 9, 1976.

DEPTH (cm)	WILKIE POINT J-51 UNDISTURBED	WILKIE POINT J-51 DISTURBED (sump)	DYER BAY 1-59 UNDISTURBED	DYER BAY 1-59 DISTURBED (sump)
Surface*	5.0	4.5	1.5	2.0
10	4.5	4.0	3.5	3.5
20	4.0	2.5	4.5	4.0
30	2.5	1.0	4.0	3.5
40	1.0		3.0	2.5
FROST TABLE 16/8/76	47cm	35cm	75cm	75cm
VEGETATION	Polar Desert		Polar Desert	
MATERIALS	Sandstones and sands, Wilkie Point Formation		Sand and gravel, Beaufort Formation	

*Temperatures taken with YSI thermistor probe and telethermometer.

TABLE 2. Typical active layer temperature (°C) and thaw depth in disturbed and undisturbed terrain at Wilkie Point J-51 and Dyer Bay 1-59 wellsites, Prince Patrick Island, August 16, 1976.

PROBLEMS	EXAMPLES	COMMENTS
A. Non-containment problems during drilling.	Bent Horn 1-01	Two sumps constructed.
	Chads Creek B-64	Three sumps constructed.
	Parsons Lake N-10	Spill into lake; gully erosion; legal action.
B. Melt-out problems during summer drilling.	Bent Horn A-02	Undermining of rig.
	Parsons Lake D-20	Leakage of fluids.
	Parsons Lake A-44	Thermokarst/enlargement of sump.
C. Restoration problems:		
(a) sump infilling and volcano effect;	Parsons Lake A-44	Large gravel cap constructed.
(b) sump subsidence and collapse	Drake D-68; Beaverhouse Creek N-13	
(c) lack of infill	Niglintgak M-19; H-30; Taglu D-55	
(d) leakage of fluids	Parsons Lake D-20	
(e) poor geographic locations	Drake B-44; Castel Bay C-68; Hecla J-60; Kumac J-06	
(f) excessive terrain disturbance	Bent Horn A-02; Orksut 1-44	

TABLE 3. Analysis of sump problems, with examples documented in text.

OPERATING PROCEDURES	NUMBER OF WELLSITES VISITED	NUMBER WITH SUMP/OTHER PROBLEMS	EXAMPLES
1. One season winter drilling (Start and finish of operation, including site restoration, within single winter drilling season).	24	4	Hecla 1-69 Drake B-44 Bent Horn 1-01
2. Two season winter drilling (Start and finish drilling within one winter season. Sump left open during summer and site restoration in second winter).	12	6	Parsons Lake N-10 Parsons Lake A-44 Chads Creek B-64 Hecla J-60
3A. Summer drilling (Operation begins in winter and continues into summer. Site restoration in second winter).	7	4	Taglu D-55 Bent Horn A-02
3B. Summer drilling (Operation begins in mid-summer and finishes in following winter).	4	3	Drake D-68 Niglintgak M-19

TABLE 4. Classification of exploratory wellsites visited according to operating procedures and occurrence of sump and/or other problems. See text for explanations.

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NAME	COMPANY	LATITUDE LONGITUDE	LOCATION	DEPTH	IAND FILE	COMPLETION
Ikkariktok M-64	Columbia et al Amoco	72° 23'N 121° 50'W	Banks Island	4,226'	N73A 568	1974
Orksut 1-44	Deminex CGDC Foc Amoco	72° 23'N 122° 42'W	Banks Island	10,040'	N72A 216	1973
Sherard O-54	Dome Arctic Ventures	76° 13'N 108° 20'W	Melville Island	4,030'	N73A 540	1973
Tiritchik M-48	Elf Texaco	72° 47'N 120° 44'W	Banks Island	7,268'	N73A 591	1974
Kusrhruk D-16	Elfex et al	73° 25'N 120° 05'W	Banks Island	12,500'	N74C 807	1975
Wilkie Point J-51	Elfex et al	76° 30'N 117° 19'W	Prince Patrick Island	7,700'	N74A 920	1975
Dyer Bay 1-59	Elf	76° 08'N 121° 48'W	Prince Patrick Island	10,405'	N75A 005	1976
Parsons A-44	Gulf Mobil	68° 53'N 133° 40'W	Mackenzie Delta (Pleistocene)	11,600'	N75A 944	1975
Parsons N-10	Gulf Mobil	68° 59'N 133° 31'W	Mackenzie Delta (Pleistocene)	10,515'	N73A 328	1973
Taglu D-55	Imperial	69° 24'N 134° 59'W	Mackenzie Delta (Modern)	12,158'	N71A 0233	1972

Appen. 1. List of exploratory wellsites visited in 1976 and 1977, and described in this report.

NAME	COMPANY	LATITUDE LONGITUDE	LOCATION	DEPTH	IAND FILE	COMPLETION
Wagnark G-12	Imperial	69° 11'N 133° 18'W	Mackenzie Delta (Pleistocene)	11,718'	N73A 374	1973
Drake Point N-67	Panarctic	76° 26'N 108° 55'W	Melville Island	8,454'		1970
Drake Point L-67	Panarctic	76° 26'N 108° 55'W	Melville Island	10,671'		1970
Drake Point K-67	Panarctic	76° 26'N 108° 55'W	Melville Island	3,198'		1970
Hecla J-60	Panarctic Homestead	76° 19'N 110° 19'W	Melville Island	11,865'		1970
Central Dome H-40	Panarctic	78° 19'N 96° 15'W	Amund Ringnes Island	11,030'		1971
Hecla F-62	Panarctic Tenneco et al	76° 21'N 110° 24'W	Melville Island	4,000'	N72A 181	1972
West Amund 1-44	Panarctic Gulf	78° 23'N 97° 50'W	Amund Ringnes Island	3,137'	N72A 076	1972
Drake F-16	Panarctic Tenneco et al	76° 25'N 108° 35'W	Melville Island	4,850'	N72A 122	1972
Drake B-44	Panarctic Tenneco et al	76° 23'N 108° 16'W	Melville Island	4,580'	N72A 198	1972

Appen. 1(continued).

NAME	COMPANY	LATITUDE LONGITUDE	LOCATION	DEPTH	IAND FILE	COMPLETION
Hecla 1-69	Panarctic Tenneco et al	76° 18'N 110° 23'W	Melville Island	4,779'	N73A 353	1973
North Sabine H-49	Panarctic Homestead	76° 48'N 108° 45'W	Melville Island	12,505'	N73A 541	1974
Drake Point D-68	Panarctic et al	76° 27'N 108° 55'W	Melville Island	17,766'	N73A 442	1974
Sirius K-28	Panarctic Home Tenn et al	79° 17'N 103° 43'W	Ellef Ringnes Island	9,420'	N73A 559	1974
Bent Horn N-72	Panarctic Tenn et al	76° 21'N 103° 58'W	Cameron Island	14,379'	N73A 500	1974
Drake E-78	Panarctic POR Homestead	76° 27'N 108° 29'W	Melville Island	4,446'		1974
Castel Bay C-68	Panarctic Tenn et al	74° 07'N 120° 49'W	Banks Island	9,530'	N74A 758	1975
Chads Creek B-64	Panarctic et al	76° 23'N 109° 54'W	Melville Island	16,523'	N74A 850	1975
Collingwood K-33	Panarctic Tenn et al	76° 32'N 108° 43'W	Melville Island	6,713'	N74A 845	1975
Bent Horn A-02	Panarctic	76° 21'N 103° 58'W	Cameron Island	N/A	N75A 145	1976

Appen. 1 (continued).

NAME	COMPANY	LATITUDE LONGITUDE	LOCATION	DEPTH	IAND FILE	COMPLETION
Key Point O-51	Panarctic	104° 22'W 76° 10'N	Vanier Island	N/A	N75A 146	1976
Bar Harbour E-76	Panarctic Elf	74° 17'N 123° 54'W	Banks Island	6,027'	N75A 008	1976
Mocklin Point D-23	Panarctic	78° 22'N 104° 44'W	Ellef Ringnes Island	9,193'	N75A 042	1975
Bent Horn F-72A	Panarctic	76° 21'N 103° 58'W	Cameron Island	10,716	N75A 049	1975
Bent Horn 1-01	Panarctic	76° 21'N 103° 58'W	Cameron Island	N/A	N76A 370	1977
Charles Point G-07	Panarctic	103° 5'W 76° 27'N	Cameron Island	N/A	N76A 367	1977
Beaverhouse Creek H-13	Shell	68° 22'N 135° 33'W	Mackenzie Delta (Richardson Mts.)	12,295'	R-1260-16-6W	1971
Niglintgak H-30	Shell	69° 19'N 135° 20'W	Mackenzie Delta (Modern)	7,817	N72A 119	1973
Kugpik O-13	Shell	68° 52'N 135° 18'W	Mackenzie Delta (Modern)	12,101'	N72A 271	1973
Kumak C-58	Shell	69° 17'N 135° 13'W	Mackenzie Delta (Modern)	11,582	N73A 388	1973

Appen. 1 (continued).

NAME	COMPANY	LATITUDE LONGITUDE	LOCATION	DEPTH	IAND FILE	COMPLETION
Kumak J-06	Shell	69° 15'N 135° 00'W	Mackenzie Delta (Modern)	11,420'	N73A 494	1974
Napoiak F-31	Shell	68° 20'N 134° 53'W	Mackenzie Delta (Modern)	5,015'	N74A 660	1974
Niglintgak M-19	Shell	69° 18'N 135° 19'W	Mackenzie Delta (Modern)	13,200'	N73A 496	1975
Kumak K-16	Shell	69° 15'N 135° 03'W	Mackenzie Delta (Modern)	12,170'	N74A 839	1975
Kugpik L-24	Shell	68° 53'N 135° 22'W	Mackenzie Delta (Modern)	9,242'	N74A 817	1975
Niglintak B-19	Shell	69° 20'N 135° 16'W	Mackenzie Delta (Modern)	N/A	N75A 002	1975
Ulu A-35	Shell	68° 42'N 135° 48'W	Mackenzie Delta (Modern)	N/A	N75A 161	1976

Appen. 1 (continued).

WELLSITE	AGE OF DRILLING	AGENCY	DEPTH	COMMENTS
Simpson Test Well No 1	Pre-1953	U.S. Navy	7000'	No sump
Simpson Test Well No 29	Summer 1949	U.S. Navy	c3000'*	No sump
Old Tapagoruk	Pre-1953	U.S. Navy	c4000'*	No sump
Old Fish Creek	Summer 1950	U.S. Navy	7000'	No sump
South Simpson No 1	Winter 1976-77	Husky Oils	8700'	Sump
Cape Halkett No 1	March-May 1975	U.S. Navy (Husky Oils)	9900'	No sump
East Teschepuk Lake No 1	March-May 1976	Husky Oils	10600'	Sump
South Harrison	Winter 1976-77	Husky Oils	12800'	Sump

*Exact data unavailable.

Appen. 11. List of wellsites visited in NPR-4, Alaska, June 28-30, 1977.

Important:- Do not remove this card from pocket
DATE DUE
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